$\nu_\mu \rightarrow \nu_e$ oscillation study in MINOS

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Outline:

- Introduction
- ν_e identification in the MINOS detectors
- Background studies using the MINOS near detector
- Conclusion

Goal of $\nu_\mu \to \nu_e$ oscillation study: measuring θ_{13}

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$$

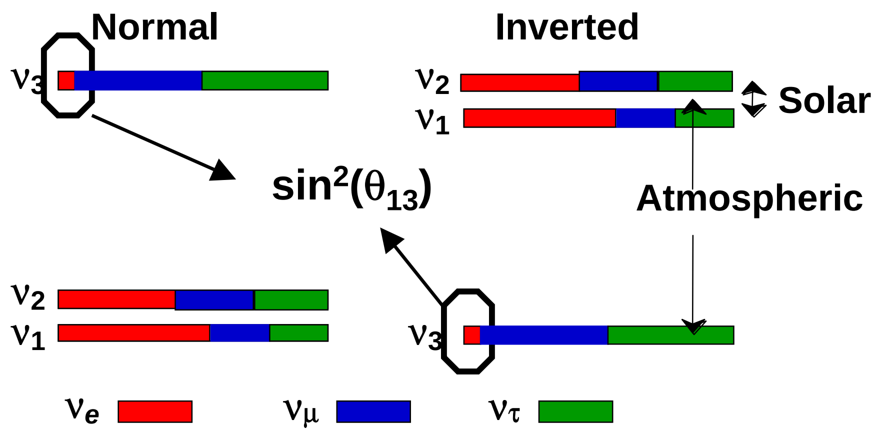
$\nu_i = (\nu_1, \nu_2, \nu_3, \ldots)$: mass eigenstates with mass $m_i = (m_1, m_2, m_3, \ldots)$, $\Delta m_{ij} = m_i^2 - m_j^2$

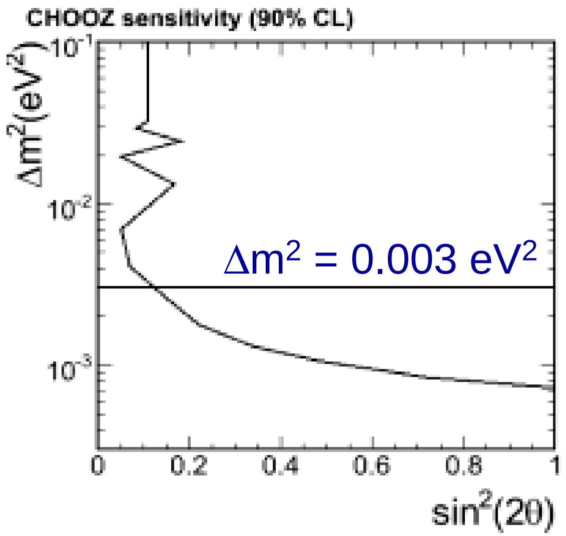
$\nu_\alpha = (\nu_e, \nu_\mu, \nu_\tau, \ldots)$: flavor eigenstates

MNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & \boxed{U_{e3}} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$|U_{e3}|^2 = \sin^2(\theta_{13})$





Results from CHOOZ

- No evidence of oscillations in $\bar{\nu}_e$ disappearance mode
- $\sin^2(2\theta_{13}) < 0.12$ at 90% CL for $|\Delta m_{32}|^2 = 3\times10^{-3} eV^2$

Goal of $\nu_\mu \to \nu_e$ oscillation study: measuring θ_{13} (continued)

$P(\nu_\mu \to \nu_e) = \sin^2(\theta_{23}) \sin^2(2\theta_{13}) \sin^2(1.27\ \Delta m_{13}^2\ L/E)$

- ignoring matter effect, solar terms and CP violating phase

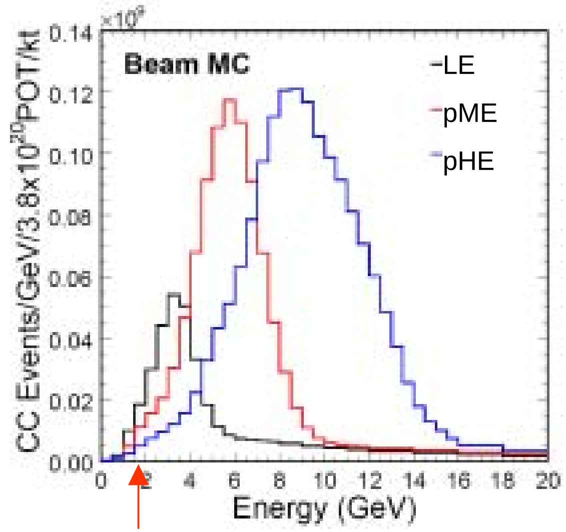
- E: neutrino energy(GeV)

  L: distance neutrino travels(km) – 735km

  • Neutrino beam provided by 120 GeV protons from the Fermilab Main Injector.

  • A Near detector at Fermilab to measure energy spectrum and understand the background

  • A Far detector deep underground in the Soudan Mine, Minnesota, to search for ν_e signals from oscillation



Position of osc. maximum for Δm^2=0.003 eV^2

signal/background separation in the MINOS detectors

MINOS far detector: 5.4 kton mass, 8×8×30m, 484 steel/scintillator planes

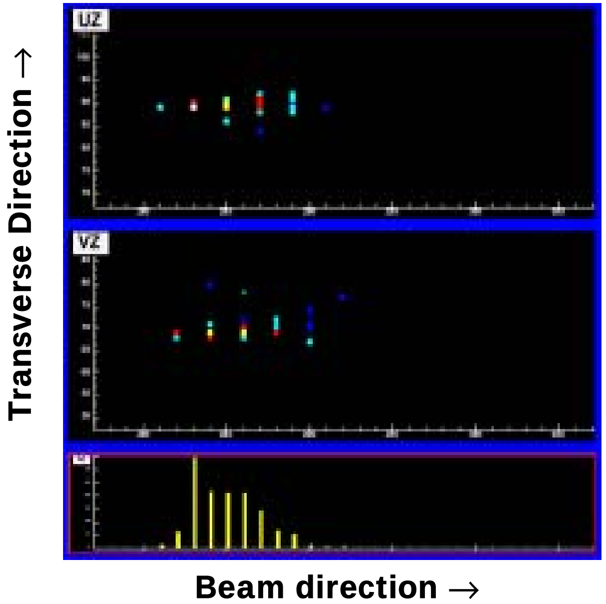
MINOS near detector: 1 kton mass 3.8×4.8×15m, 282 steel and 153 scintillator planes

steel thickness: 2.54cm ~ $1.44X_0$

strip width: 4.12cm (Molière radius ~3.7cm)

Signal:

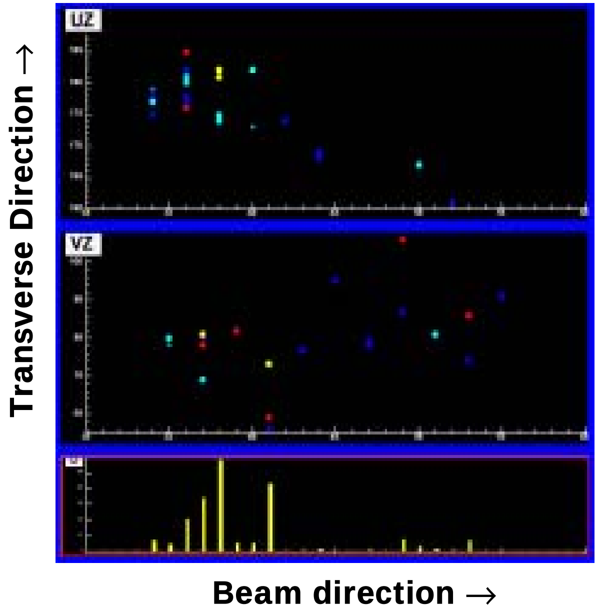
ν_e CC interaction: $\nu_e + N \rightarrow e + X$



- **compact, with typical EM shower profile**

Primary Background:

NC interaction $\nu_l + N \rightarrow \nu_l + X$



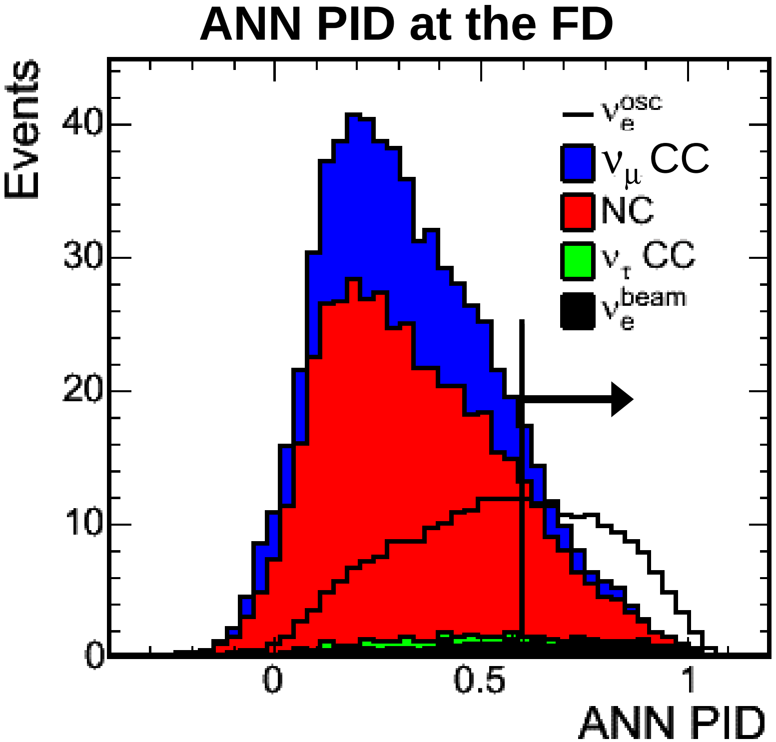
- **often diffuse and scattered**

Other background components: beam ν_e, high-y ν_μ CC interactions, oscillated ν_τ in the far detector

signal/background separation in the MINOS detectors (continued)

A lot of effort has been devoted to the shower reconstruction in order to distinguish between electromagnetic shower and hadronic shower.

A few different discriminating techniques have been tried to enhance signal/background separation: cuts, Multivariate Discriminant Analysis, ANN based on shower sampling, ANN based on shower reconstruction.



One example analysis – Neural Net

$\sin^2(2\theta_{13}) = 0.04$, $|\Delta m_{31}|^2 = 2.5\times10^{-3}eV^2$, $\sin^2(2\theta_{23}) = 1$, POT=15e20

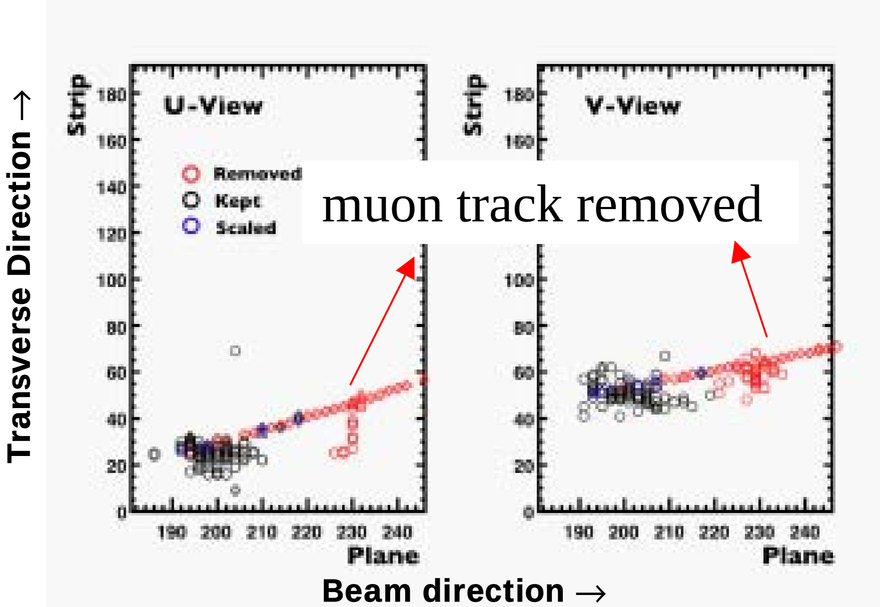
ν_e^{osc} was scaled up by a factor of 10 for clarity.

Figure of Merit = signal/sqrt(background) = 1.26

ν_μ CC	NC	ν_e^{beam}	ν_τ CC	Total background	ν_e^{osc}
15.6	54.1	10.6	4.3	84.6	11.6

Estimating NC background using the muon-removal technique

Remove the muon in a selected ν_μ CC event and use the rest of the event as a fake NC event.



This technique is a direct estimate of the NC background after some corrections, provided that the difference in hadron multiplicity does not change the event topology too much:

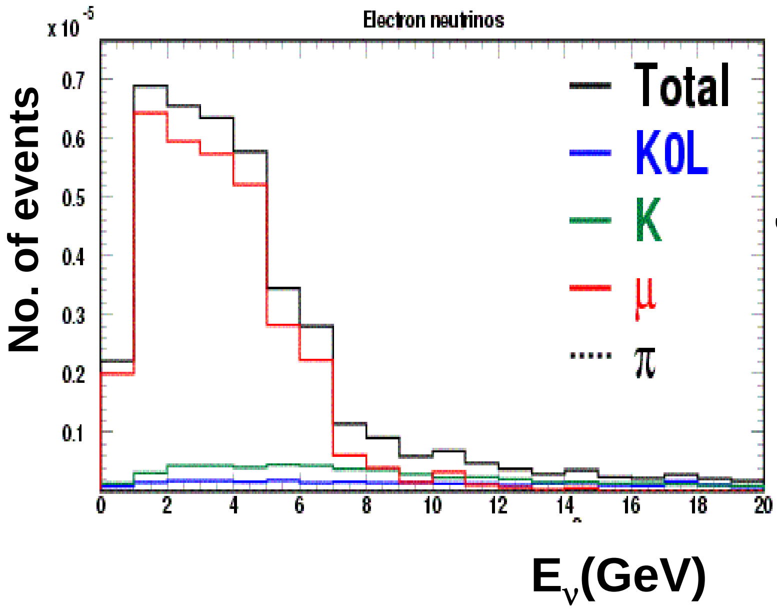
- ν_μ CC selection efficiency and purity
- ν_μ CC oscillation probability in the far detector
- CC/NC cross section ratio

Constraining the ν_e flux from $\bar{\nu}_\mu$ measurements

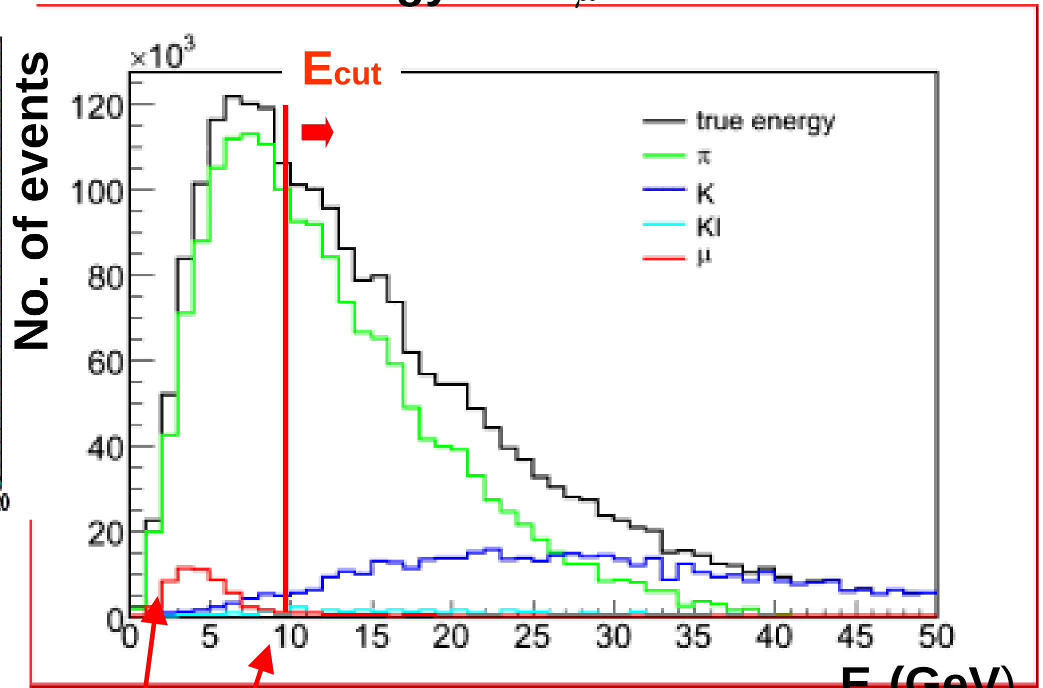
Primary source of low energy beam ν_e is $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

a measurement of low energy $\bar{\nu}_\mu$ can be used to constrain the ν_e flux

True energy of beam ν_e at the ND



True energy of $\bar{\nu}_\mu$ at the ND



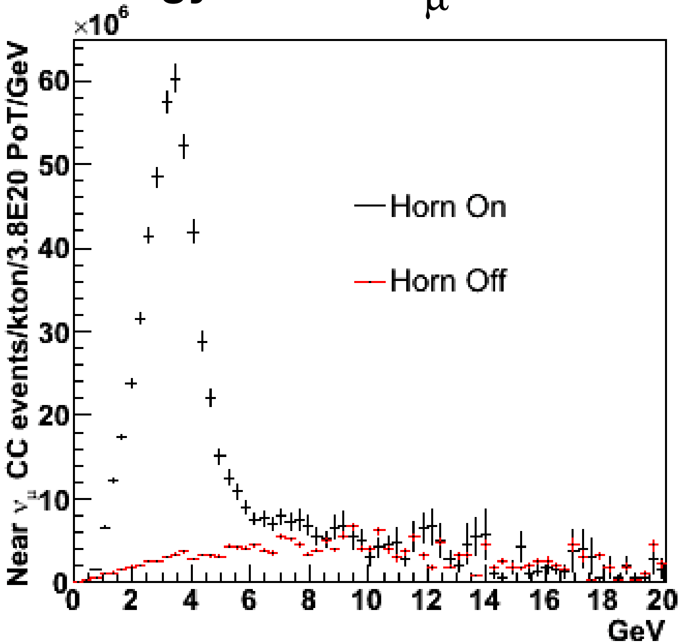
No $\bar{\nu}_\mu$ from μ+ above this energy (E_{cut})

This is what we are trying to measure

The majority of beam ν_e background in the energy region we are interested in is from μ^+ decay

Estimating background uncertainties using horn off data

True energy of true ν_μ at the ND



If we turn off the horns, the pions will not get focused and the peak in the neutrino energy spectrum will disappear.

After we apply the same ν_e selection cuts, we will get a NC-enriched sample.

$$N^{on} = N_{NC} + N_{CC} + N_e \qquad (1)$$
$$N^{off} = r_{NC} * N_{NC} + r_{CC} * N_{CC} + r_e * N_e \qquad (2)$$

Can be solved to get NC and ν_μ CC background

N^{on}, N^{off}: selected ν_e candidates with horn on and horn off – will be measured

N_e: beam ν_e background with horn on – from MC

$r_{NC(CC,e)} = N_{NC(CC,e)}^{off} / N_{NC(CC,e)}$ – from MC

N_{NC}, N_{CC}: NC, ν_μ CC background with horn on – will be calculated based on eqn. (1) and (2)

Estimating background uncertainties using horn off data (continued)

The advantage of this technique: can separate different backgrounds and estimate the uncertainty of each component.

MC simulation: 1.5e18 POTs horn off and ~1e19 POTs horn on data:

$N^{on} = 608.4 \qquad \delta N^{on} = 0$

$N^{off} = 189.1 \qquad \delta N^{off} = 13.8$

$r_{NC} = 0.425 \quad r_{CC} = 0.107 \quad r_e = 0.165$, $\delta r/r = 10\%$

$N_e = 96.8 \qquad \delta N_e = 19.4$ – assign a 20% systematic error

Expected background at Near Detector for 1.5e18 POTs

	Tot. bg.	NC	ν_μ CC	ν_e^{beam}
background	608.4±94.2	361.5±64.2	150.1±66.1	96.8±19.4
error	15.5%	17.8%	44.0%	20%

Other contributions and ongoing work:

- hand scanning – an independent cross check, valuable inputs to automated analysis
- analysis tools development
- cosmic ray background study
- ν_e -related hadron production study

Sensitivity (90% CL Exclusion)

- With our current data set, we will be able to approach CHOOZ's limit.
- With five times more data, we will improve CHOOZ's limit by a factor of 2. If θ_{13} is not too small, we may see a signal and make the first measure of θ_{13}.